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Abstract

High temporal and spatial resolution measurements in the boundary of the DIII–D tokamak show that edge localized modes (ELMs) are composed of fast bursts of hot, dense plasma that travel radially starting at the separatrix at ~450 m/s and rotate in the scrape off layer (SOL), convecting particles and energy to the SOL and walls. The temperature and density in the ELM plasma initially correspond to those at the top of the density pedestal but decay with radius in the SOL. The temperature decay length (~1.2-1.5 cm) is much shorter than the density decay length (~3-8 cm), which in turn decreases with increasing pedestal density. The local particle and energy flux at the wall during the bursts are 10-50% (~1-2 $\times 10^{21}$ m^{-2} s^{-1}) and 1-2% (~20-30 kW/m^2) respectively of the LCFS average fluxes, indicating that particles are transported radially much more efficiently than heat.

JNM keywords: PO500, PO600

PSI-16 keywords: DIII–D, Edge Plasma, Cross-field transport, Intermittent transport

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I. Introduction

High performance tokamak discharges operate in ELMing H–mode to combine high-energy confinement with adequate particle exhaust. The edge localized mode (ELM) instability also carries a considerable amount of particles and heat from the pedestal region into the scrape-off layer (SOL) towards the divertor region and other plasma facing components (PFCs), possibly limiting their lifetime and causing the release of impurities into the plasma. According to accepted scalings, Type I ELMs are expected to exceed the ITER PFC damage threshold (40-50 MJ m^{-2} t^{-1}) by factors of 5 or more,[1] resulting in a divertor lifetime of <1 full discharge! It is important to invest a significant effort to study ELMs the ELM dynamics in the SOL in order to envision ways of controlling their interaction with the PFCs.

A number of theoretical ELM studies[2] have emphasized the linear regime of dominant modes[3] (coupled "peeling-ballooning" modes) are driven by parallel current (J_{ped}) and the pressure gradient (p'_{ped}). These intermediate-n peeling-ballooning modes, whose linear phase can be calculated using the ELITE code, impose limits on the pedestal height, which are functions of the pedestal width, plasma shape, collisionality, safety factor and other equilibrium details. Preliminary nonlinear studies[4] suggest that during the ELM, filaments will grow in the pedestal region and travel across the separatrix into the SOL, carrying particles and heat with them. This paper provides information on ELM structure and propagation that can be used to improve the models.

II. Experimental setup

Experiments to characterize ELMs on the DIII–D tokamak[5] were carried out in H–mode discharges featuring Type I ELMs with plasma current $I_p = 1.4$ MA, toroidal field of

$B_T = 1.7$ T at the axis, $R = 1.7$ m and neutral beam heating power of up to 4.5 MW. Lower single-null divertor geometry with ion Grad-B drift toward the lower divertor was used. The density was increased in a sequence of discharges, from $\langle n_e \rangle / n_G = 0.40$ to 0.8. (n_G is the Greenwald limit) The principal measurements were made by the fast radiometer array[6] (DISRAD2), a fast scanning probe,[7] Beam Emission Spectroscopy[8] (BES), reflectometry[9] and CER[10]. The fast scanning probe array features five tips that sense current I, saturation current, I_{sat}, and floating potential, Φ_f. A ≈ 250 kHz bandwidth T_e measurement[11] is used to resolve the temperature inside the ELMs. The BES system, configured as a 5×6 fiber array, was located at the edge of the plasma in the midplane to provide fast ($1\ \mu$s) 2-D imaging of the density. The DISRAD2 measures absolutely calibrated photon intensity along 30 poloidally separated view chords at a rate of 100 kHz and a photon energy response of 1 eV to 5 keV.

A. General ELM characterization

Inversion of the DISRAD2 data (Fig. 1) shows the integrated ELM radiation for various plasma regions as a function of time measured from the beginning of an arbitrary ELM, or t_0. The radiation rises first on the outer SOL indicating low field side ELM formation, it then rises in the inner SOL and thereafter in the divertor. Two frames from BES taken at an arbitrary time near an ELM onset, t_0^{BES} and 16 μs later ($t_0^{\mathrm{BES}} + 16\ \mu$s) and shown in Fig. 2, feature an ELM as a positive density feature appearing at the bottom of the frame and moving upward to the center. The data shown is the deviation from the average value and in the color scheme, white represents average (or background) density and red and blue represent positive and negative fluctuations, black indicates saturation. The LCFS is indicated by a solid vertical line. The ELM includes plasma ejections produced near the separatrix that then move radially at nearly 7 km/s (the BES measurements were made in a different set of discharges that those otherwise discussed in this paper). Radial propagation into the SOL, seen by reflectometry[12], shows ELMs with a velocity that peaks at ~500 m/s and decays to ~120 m/s in the SOL. Probe measurements of $V_r = E \times B / B^2$ agree with reflectometry[12].

The ELMs have a complex spatio-temporal time structure, consistent with BES data, that is observed as multiple bursts in the temperature and density data taken by probes, shown in

Fig. 3. The high time resolution data, displayed in a 12 ms window that arbitrarily spans the ELM duration. The ELM plasma features peak n_e values corresponding to those at the top of the density pedestal (~3×10^{19} cm^{-3}) if the spatial decay is accounted for. The ELM peels off from the top of the density pedestal. The radial decay of the ELM peak density and temperature with distance from the LCFS varies with density shown in Fig. 4. At high n_e ($n_e/n_G = 0.85$) the density decay length, $L_N \approx 3.8$ cm while the temperature decay length, L_T is ~1.2 cm. At $n_e/n_G = 0.45$, L_N and L_T are 13 cm and 1.3 cm, respectively. The particles in the ELM travel unhindered towards the wall at low densities while at high density, the particles are quickly dissipated. The heat in the ELM seems to be dissipated rapidly with radius, irrespective of the pedestal density, and consistent with IR camera results.

Probe and reflectometry data at the midplane indicate plasma convected at velocities of ~450 m/s that slow to ~120 m/s into the SOL within 0.20 ms. At the highest speed, the ELM would strike the wall (6 to 7 cm from the LCFS) in ~0.15 ms, but due to the deceleration, the total radial transit time is closer to 0.3 ms. The ***local*** peak heat and particle radial flux convected by the ELM towards the wall are $\Gamma_r = nV_r$ and $Q_r = 2 \times 3/2\, nTV_r$ respectively. Due to bursts, the ELM-induced ***local*** convected radial heat flux at the LCFS is ~80% of the average [calculated as $(P_{in}-P_{rad})/\tau_E$xArea] at $\langle n_e \rangle / n_{GW} = 0.8$ and ~60% at $\langle n_e \rangle / n_{GW} = 0.45$. The heat flux reaching the wall (Table I), is only a ~2% fraction of the LCFS heat flux, consistently with the short (~1.5 cm) T_e radial decay, most of the heat flux is transported along the magnetic field and strikes the divertor floor. The ELM local convected radial particle flux due to the pulses at the wall is 10-50% of the LCFS local average radial flux, or $\sim 1.6 \times 10^{21}$ m^{-2} s^{-1}, consistent with the long density decay length (~3-8 cm). Table I indicates that the ELM local peak particle flux at the wall is quite similar for all densities due to the fact that at higher pedestal densities the ELM plasma density increases but the decay length becomes shorter.

III. Interpretations of the ELM dynamics data

Assuming mainly radial motion of the ELMs and using the measured radial ELM velocity, V_r, at the LCFS (~450 m/s), the radial extent of each front is estimated as $\Delta r = V_r \times \Delta t$, where Δt is the duration of the pulse. Radial extents of 2 to 5 cm per pulse are obtained from the pulse duration (~20 to 40 μs long). Gaps lasting ~130 to 140 μs are seen between pulses, sometimes followed by a longer gap of ~ 800 μs between trains of pulses. The ELM comes from the LCFS in well-defined bursts that substantially fill the SOL (6 to 7 cm gap) with dense plasma. This paradigm is hard to reconcile with the fact that many diagnostics in all toroidal and poloidal locations see the ELM promptly within a small time delay of ~ 100 μs.

Another possibility is that the ELM plasma is also rotating toroidally. The CER[31] toroidal speeds during an ELM at radii straddling the LCFS are shown, together with a rotation profile [Fig. 5(b)] before ($t_0 - 1$ ms) and during (t_0) an ELM, where t_0 is determined by the rise of the fast D_α signal in the divertor. The onset of an ELM is concomitant with a transient increase of toroidal velocity and ion temperature (all from carbon) further out and into the SOL [Fig. 5(b,c)], which lasts «1 ms, consistent with the radial ELM plasma travel time (~0.3 ms). The peak toroidal velocity and ion temperature of the radial transient corresponds to that of the innermost chord pre-ELM velocity, supporting that ELMs originate at the pedestal top. The CER-measured toroidal velocity is ~30 km/s in the SOL, corresponds to ~ 650 μs period, longer than the expected ELM plasma radial travel time of 200 to 300 μs, so the ELM plasma does not have time to fully rotate before hitting the wall. Once the rotation assumption is considered, Fig. 3 can be re-examined. The initial density bursts are separated by ~ 135 μs, followed by a ~ 450 μs gap before the bursts start again. This could be interpreted as three filaments rotating by the probe and returning with a period $T = 800$ μs while decaying by parallel transport.

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Table 1. Radial particle (T_r^{ELM}) and heat (Q_r^{ELM}) fluxes due to an ELM at the LCFS and the wall for low density $\langle n_e \rangle / n_{GW} = 0.45$ high density $\langle n_e \rangle / n_{GW} = 0.8$ discharges

$\langle n_e \rangle / n_{GW} = 0.8$	$\Gamma_r^{ELM} (m^{-2} s^{-1})$	$Q_r^{ELM} (J\, m^{-2} s^{-1})$
LCFS	1.0×10^{22}	1,800,000
Wall	1.5×10^{21}	21,600
$\langle n_e \rangle / n_{GW} = 0.45$	$\Gamma_r^{ELM} (\#m^{-2} s^{-1})$	$Q_r^{ELM} (J\, m^{-2} s^{-1})$
LCFS	5.6×10^{21}	1,323,000
Wall	1.8×10^{21}	27,000

Figure captions

Fig. 1 Inversion of DISRAD2 data from a single ELM (Type I) showing radiation peaking in the outer SOL, in the inner SOL, later at the inner divertor, and at the outer divertor, demonstrating ELM propagation over the top of the plasma into the inner divertor leg.

Fig. 2. Frames from BES showing 2-D density plots and taken every 1 μs. The Type I ELM starts at t_0. A second frame is taken 16 μs thereafter to illustrate ELM characteristics. The ELM shows a poloidal structure that becomes quite complex. Radial and poloidal motion of ejecta is seen.

Fig. 3. High time resolution probe density data for a low discharge density $(n/n_g = 0.4)$ showing the spatio-temporal complexity of ELMs. The successive bursts of high density lasts ~30 μs and appear at fairly regular intervals (~140 μs). The intervals can show significant gaps of ~300-400 μs between groups of bursts.

Fig. 4. Radial variation of the ELM ***burst*** density and temperature values obtained from probes for (a) high density and (b) low density discharges. The temperature decays quickly with radius in both cases, but the density decay length is longer at low density.

Fig. 5. (a) CER data showing the toroidal rotation velocity of carbon ions for 7 radial positions inside the LCFS and in the SOL. A floor D_α signal [(a) top] is used as a fiducial. Profiles of rotation velocity (b) and ion temperature (c) taken during the ELM (t=0) and before the ELM (t=–1) support the idea that the plasma at the top of the density pedestal is expelled into the SOL and rotates toroidally in the near SOL before being damped in the far SOL.